TEST EFFECTIVENESS TREND OBSERVATION

Relative Effectiveness Of Thermal Cycle And Thermal Dwell Testing

CONCLUSION:

Based on the results of this study, it is concluded that much of the currently used thermal cycle testing should be eliminated. Available data support the hypothesis that the failures following the first thermal cycle are from a separate population than those requiring thermal changes for screening. Since most of the effectiveness in precipitating thermal change failures is in the first cycle and fatigue damage accumulates rapidly with the number of cycles, the total number of thermal cycles should be minimized. Furthermore, extended durations at temperature extremes are most effective at exposing the other population of failures. Therefore, at most, thermal testing should consist of a low number of thermal cycles (1 or 2) with extended durations, or dwells, at both temperature extremes.

DISCUSSION:

Introduction

Supplier testing is conducted to find defects before products are utilized in their ultimate usage environments. This testing is intended to precipitate defects (both design and workmanship) prior to final delivery. Testing under thermal conditions is one of the most utilized methods for screening out these defects. There are two primary types of thermal testing which are most commonly employed: thermal cycling and fixed temperature burn-in. There are different opinions as to which of these are the most effective as screens. In order to understand the relative effectiveness of these two types of thermal screens, a joint report between LMSC and JPL was written [0]. For those interested in the findings of this report (Thermal Testing Study Report, JPL D-11958), copies may be requested from the Library Archive Center at the Jet Propulsion Laboratory.

Reasons for Thermal Testing

The report establishes the reasons for thermal testing based on failure physics and on the well-established need to accomplish design qualification, design verification and infant mortality (workmanship) screening. These infant mortality defects are further divided into thermal change failures and burn-in failures. This differentiation of defects into these two categories is useful in understanding what the failure data

later reveals. In addition, the different objectives of the thermal testing programs are also discussed in further detail, including the various design qualification and verification objectives such as accelerated aging, verification of thermal control performance and verification of various other types of functional performance.

Analysis of Existing Thermal Cycling Data

Figure 1 shows a typical thermal cycle plot. There are a large number of failures on the first cycle relative to the second and subsequent cycles. This Plot appears to apply universally to electronic and electro/mechanical assemblies that are thermal cycle tested. The large number of failures found on the first cycle appear to be from a different population than failures in subsequent cycles.

By considering the first cycle failures as a separate population, one can see that there is little improvement from cycles 2 through n. The dotted best fit curve (of cycles 2-n) shows that improvement is occurring but at a slow rate. The large number of failures found on the first cycle are mostly Thermal Change Failures, while Burn-in Failures are found on subsequent cycles and are not decreasing nearly as quickly as a function of time. The number of Thermal Change Failures found on subsequent cycles may be trivially small when compared to the time related Burn-in Failures. If it turns out that subsequent failures contain very few Thermal Change Failures, is there another way to eliminate them that is superior to thermal cycling? Can a similar slope of failure precipitation be expected from testing the assembly at a fixed ambient temperature for example? An advantage of converting to a fixed ambient temperature is that we terminate the damaging effects from wearout due to thermal cycling fatigue.

It has been an almost universal practice in technical papers written on thermal cycling to include the first cycle data when establishing curves of best fit even though such curves do not match the data. This is illustrated by the solid curve of Figures 1A and 1B which clearly does not match the data. A whole series of strength equations have been developed using this method. These equations are designed to show the strength of the failure rate relative to the number of thermal cycles. While the strength equations are valid relative to the curves, they are not valid relative to the failure data which is much lower. The strength equations imply a strong relationship between failures and cycles 2 through 10 that is not supported by the data in the publication

RADC Strength Equations

Strength Equations based on the Number of Thermal Cycles published by RADC were developed using data that was derived from James R. Anderson's 1981 report on 6 avionics systems [1]. The original data was published as combined vibration and thermal cycling data for the Heads Up Display Sets. This is used in many subsequent publications to show typical thermal cycles to failure

expectations but such publications fail to point out that sine vibration is included in each cycle[2,3]. The same chart was then used to develop strength equations for the optimum number of thermal cycles in RADC-TR-86-138. In this later publication, the chart was labeled as Thermal Cycle (Only) data and strength equations were then developed and mistakenly implemented assuming the data was only from Thermal Cycle screening. The 1993 upgrade to MIL-HDBK-344A continues to carry the erroneously labeled chart and still uses the same faulty strength equation[4]. What we have then is the current use of strength equations based on erroneous assumptions about 18 year old data. As shown in the detailed report, part failure rates have improved by a factor of over 100 to 1 during this same 18 year period. That improvement alone should be enough to invalidate strength equations based on such old data.

IES Screening Cycle Charts

The mistake of erroneously labeling combined vibration and thermal cycling data as only thermal cycling data can also be found in IES publications. The Environmental Stress Screening of Electronic Hardware (ESSEH) Guidelines for Assemblies for 1981 shows the number of screening cycles vs Percent Fallout for a number of programs and implies that this is thermal cycled data[5]. See Figure 2. From the detailed data contained in this publication, it can be seen that only one program, the Troop Radio, is a true chart of thermal cycle fall out. The rest contain vibration failures in each cycle. The chart of Figure 2 was reprinted by the IES in their screening guidelines, ESSEH for 1984, but erroneously labeled as being the Number of Temperature Screening Cycles[6]. Ever since then, many people have relied on conclusions from this misinterpreted data. Looking at the erroneously labeled 1984 chart, one would be led to believe that at least 10 thermal cycles are required as an average. However, when only the thermal cycled data from the Troop Radio is considered, we see that most of the failures occur on the first cycle with hardly any failures per cycle thereafter.

Thermal Cycle Examples that match the Universal Plot

The report then provides a number of specific case studies where data is available on the cumulative failures versus the thermal cycle at which the failures occurred. These case studies include: 1200 IBM Low Voltage Power Supplies[9], 48 Spacecraft Boxes[10], 313 Satellite Boxes[11], 216 Milstar Satellite Boxes[12], 63 Navy Standard 80 MB Disk Drive Systems[13] and 17,180 AT&T Commercial Circuit Boards[14,15,16]. A typical failure plot is shown in Figure 3[16]. In all cases except the last one, the Universal Curve of Figure 1 represents the failure distribution. In the cast of the AT&T boards, the Universal Curve applies except for the second cycle which has a larger number of failures than this curve would predict. See Figure 4. However, upon close examination, the AT&T data

included a slow transition thermal cycle for the first cycle and all of the subsequent cycles were with a faster transition rate. This AT&T data provides some evidence for the value of different transition rates in precipitating defects.

Stress Effects of Thermal Cycling

The report also examines the stress effects of thermal cycling. It is well known that fatigue life of hardware is a consumable, and that any testing of flight hardware irrevocably removes life from it. This Section provides a discussion of various fatigue issues and the associated calculations which one uses to determine the amount of fatigue life consumed. It is noted that some current testing documents utilize a low fatigue ductility exponent which can drastically underestimate the fatigue life being consumed. If one also qualified the hardware's available fatigue life with this same exponent, the problem would not be so bad but the common exponents used in these qualification programs and in the interconnect fatigue community are significantly larger. This results in underdesigned and overtested hardware.

Comparisons of Thermal Cycling and Thermal Dwell

In this section, it is acknowledged that direct comparisons of thermal cycle and thermal dwell is essentially impossible, since institutions rarely perform both types of testing as part of their environmental stress screening (ESS) program. However, evidence is presented for the effectiveness of the Jet Propulsion Laboratory (JPL) single-cycle, long dwell test program. This evidence is provided both in terms of the types of failures which occur during the test, and in terms of the mission success of programs utilizing this testing approach. In addition, curves of accumulated failure rates provide a clear illustration that JPL spacecraft have fewer cumulative failures than almost any other spacecraft. Fitting these curves to a Weibull distribution provides additional evidence that these spacecraft have achieved more acceleration past the infant mortality regime than spacecraft programs utilizing thermal cycle screening.

Additional surveys and analysis of other government data is presented along with two case studies of commercial electronics products. Both of these studies provided evidence that, after the first cycle, thermal cycle testing was marginally less effective than ambient (25_C) burn-in! In addition, data from an Aerospace Corporation study[17,18,19] of problems/failure on more than 1000 assemblies on 23 spacecraft has been analyzed and included to illustrate the types of defects which the different types of testing is precipitating. The number of failures which only thermal cycling could have exposed is consistent with the other evidence presented in the study: only one or two cycles are really needed. Additional data on the effectiveness of cold temperature soaks in also presented.

Summary, Conclusions and Recommendations

Every testing program must be re-evaluated based on parts failure rate improvement of over 100 to 1 that has occurred during the last decade. This is particularly true for thermal testing which is a key element in environmental test programs. To better understand test results we divided failures into three categories of: Thermal Change Failures, Burn-in Failures and Fatigue Failures.

We introduced a universal thermal cycle plot (Figure 1) where a large number of Thermal Change Failures are found on the first cycle. This universal curve is shown to apply to all available single transition rate, thermal cycle data. The failures from the first cycle appear to be from a different population than failures in subsequent cycles. The Burn-in Failures found on subsequent cycles appear to be more time related and are not decreasing nearly as quickly as a function of time.

Less Burn-in Failures will be precipitated during thermal cycling than would be if a fixed, elevated temperature burn-in test were run. While thermal cycling will precipitate this type of failure, it is not as efficient as using constant elevated temperature. Actual test data showed that a power-on-burn-in at ambient 25_C was superior to thermal cycling for precipitating these failures. Higher temperatures are even more efficient for producing Burn-in Failures.

An initial thermal cycle is needed to precipitate Thermal Change Failures. After precipitating these failures, the test should be converted to a fixed temperature in order to precipitate Burn-in Failures. Another advantage of converting to a fixed ambient temperature test is that it terminates the damaging effects from thermal cycling Fatigue Failures which are wearout failures resulting from fatigue stress.

Repeated thermal cycling causes fatigue which initiates and propagates cracks in solder joints and other bonding materials. There is a low initial probability for this type of failure but the probability increases as the cycles accumulate. There is also a direct relationship between the temperature delta and the applied strain which in turn is directly related to fatigue life. To avoid having products go into an early wearout, keep the number of thermal cycles low and use a low temperature delta.

In gathering data for this report, anytime the failures in cycles 2-n have been much higher than expected, further research has indicated that the data was erroneously recorded or it was found that the failures represented more than one environment. We found this to be true for a number of publications many of which keep carrying forward the same data from year to year. Of particular concern is 18 year old misapplied data being used currently as the basis for thermal cycling strength equations.

Test data shows that almost all Thermal Change Failures are precipitated on the first thermal cycle. However, it was found that some additional Thermal Change Failures

can be precipitated by changing to a new cycling speed on the second cycle. In the AT&T data on 17,180 boards tested, there were some Thermal Change Failures found with the fast thermal ramp of cycle 1 that were not found with the slow thermal ramp of cycle zero. In a technical report by Edgerton & Quart[20], it has been shown that the opposite is also true; i.e., some Thermal Change Failures are found on a slow thermal ramp that are not found on a fast thermal ramp.

Recommendations

For aerospace equipment testing it is recommended that much of the currently used cycle testing be eliminated. We recommend a thermal cycle test at the Box Level which consists of a maximum of two thermal cycles. For these two cycles, power should be applied and functional testing performed at the temperature dwell extremes and during the positive thermal ramp.

At the vehicle level, a maximum of one slow thermal cycle is recommended. At assemblies below the Box level, no thermal cycles are recommended. In particular, unpowered multiple thermal cycles at the circuit board level should be eliminated. These unpowered tests not only serve no useful purpose but are also harmful because they cause wearout due to accumulation of Fatigue Failure stresses.

It is recommended that Box level thermal cycles include both low temperature functional tests and high temperature burn-in functional tests at the chosen temperature dwell extremes. The high temperature burn-in should last for at least an equivalent of 300 hours of ambient 25_C testing. The Arrhenius equation may be used to adjust the time based on the chosen burn-in temperature.

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REFERENCES:

1   Thermal Testing Study Report, S. L. Cornford and P. Plumb, JPL D-11598 (Internal Document)
2   James R. Anderson, "Increasing the Effectiveness of Environmental Burn-in", IES Proceedings, 1981
3   AFWAL TR-80-3086, Environmental Burn-in Effectiveness, USAF., 1980
4   RADC-TR-86-149, Environmental Stress Screening, September, 1986
5   RADC-TR-86-138, RADC Guide to Environmental Stress Screening, 1986
6   MIL-HDBK-344A, Environmental Stress Screening (EES) of Electronic equipment, August, 1993
7   ESSEH, Guidelines for Assemblies, 1981

8   ESSEH, Guidelines for Assemblies, 1984

9   Jerome C. Bobrowski, "Thermal Cycle Screening of Militarized Power Supplies", IES Proceedings, 1980

10   Don Hill, "It's Time to Re-look at Testing Cost Effectiveness", IES Proceedings, 1988

11   Wayne E. Brown, LMSC, previously unpublished data, 1994

12   Paul Plumb, LMSC, previously unpublished data, 1994

13   Tim Lindgren, "Optimizing ESS Effectiveness Using Weibul techniques", IES Proceedings, 1986

14   T. Paul Parker, "ESS Case Study of High Density Surface Mount Circuit Card", IES Proceedings, 1991

15   T. Paul Parker & C. W. Webb, "A Study of Failures Identified During Board Level Environment Stress Screening", IEEE Transactions on Components etc., December, 1992

16   T. Paul Parker & G. L. Harrison, "Quality Improvement Using Environmental Stress Testing", AT&T Technical Journal, July, 1992

17   M. Gibbel, J. F. Clawson, "Electronic Assembly thermal Testing Dwell/Duration/Cycling", proceedings from Institute of Environmental Science's 12th Aerospace Testing Seminar, 1990

18   Otto Hamberg, William Tosney, Charles A. Brackin, "Satellite Environment Testing Cost Benefits", proceedings from Institute of Environmental Science's 11th Aerospace Testing Seminar, 1988

19   Otto Hamberg, William Tosney, "The Effectiveness of Satellite Environmental Acceptance Tests", proceedings from Institute of Environmental Science's 11th Aerospace Testing Seminar, 1988